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Research and development aspects on decentralized electrification options for rural household

A.A. Lahimer *, M.A. Alghoul *, Fadhil Yousif, T.M. Razykov, N. Amin, K. Sopian

Solar Energy Research Institute, Universiti Kebangsaan Malaysia, 43600 Bangi, Malaysia

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A B S T R A C T

Low income households living in the rural areas suffer from energy poverty and lack of human and economic development. Currently, many governments of less developed countries are committed in improving access to electricity. The same commitment should be adapted globally as part of human right because providing electricity access to low-income households improves health and education, generates income, increases productivity, reduces inequality, and enhances the quality of life. Rural electrification is a complicated issue because of user affordability, rural inaccessibility and remoteness, low population densities and dispersed households, low project profitability, fiscal deficit, scarcity of energy resources, population growth, lack of professionalism, and over-dependence on subsidies. The demand for electrification cannot be accomplished because of the increasing gap between rural electrification rate and population growth. Therefore, this review aims to study various decentralized household-sized energy technologies available in rural areas, such as battery, diesel generator, pedal generator, pico hydro, photovoltaic (PV) solar home system, and wind. Preference for one of the options depends on energy-source availability, economic feasibility, rural economic development, disposal of residues, nature of end-user application, and government programs and policies. Pico hydro is the preferred electricity generation source in most rural households, followed by wind, PV, and diesel generators. This paper concurs that households in rural areas will be able to afford for electricity access if the payment schedule of the electrification cost is extended and interest rates and taxes, if any, are dropped.

Contents

* Corresponding authors.
E-mail addresses: salsale3@yahoo.com (A.A. Lahimer), dr.alghoul@gmail.com (M.A. Alghoul).

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1. Introduction

1.1. Rural area characteristics

Most of low income households live in the rural areas [1–5], where the main source of income comes from pastoralism, cattle raising, agriculture [6,7], fishing [8], tourism, or forestry [9]. Rural areas are associated with dispersed and low population density [2,7], high illiteracy rate [7–10], gender inequality [10], lack of access to health care [7,11], infrastructure (roads, markets, information), and clean water supply [11], as well as energy poverty and low level of electrification rate [3,7,12]. According to [13], by 2030, 87% of the people who lack access to electricity live in rural areas and almost all of them live in developing countries. For example, in Africa, 86% of Tanzanians are not connected to the national grid [14], and majority of the population live in rural areas [6]. In Asia, only half of the Nepalese population has access to modern electricity services [3]. [8] found that even in isolated areas, such as an island, the rate of electricity consumption is associated with the level of user income; for instance, business people consume more electricity than fishermen do.

According to the study made by [15] on energy expenditure according to salary in the urban areas in South Africa, low-income households spend approximately 14% of their earnings on their energy needs. This value is approximately 4.6 times more than high-income households spend on energy [15]. People in developed countries consume 10 times more electricity than people in less developed countries do [16] because of the financial gap between people, which has increased exponentially [17]. The rate of energy consumption is related to the household welfare because of the ability to use electricity in different applications. Energy consumption can be a way of distinguishing the low-income from the high-income people [7]. Low-income people rely on traditional energy sources, such as firewood, charcoal, paraffin, and farm residues, to meet their daily energy demands for lighting, cooking, and heating because modern, sustainable energy connection is scarce [1,18,19]. Unfortunately, the people in developing countries bear a huge amount of expenditure on their energy and lighting needs more than people in the developed countries do [20,21]. In addition to the lack of road infrastructure (some only by boat) [7,22–24], access to sustainable modern energy services (connection to the power grid) will remain expensive for people living in rural areas [1,8,25] because of geographical remoteness [3] and dispersion [3,22]. These remote areas are not technologically and economically attractive to the electricity generation and distribution companies [5,8,22,26]. Grid connection seems to be difficult and impossible in some regions [3,26,27], and electrification will not be an option for rural areas in the future [27].

1.2. Rural electrification

Rural electrification is the provision of long term, reliable, and satisfactory electricity service to households in remote, rural communities [25,28,29] via grid or decentralized/centralized, renewable/nonrenewable energy resources supply. Many consider electrification as a fundamental strategy for poverty alleviation in terms of financial, energy, and sustainable developments to meet the Millennium Development Goals [9,30–32]. Rural electrification started more than a century ago in many developed countries. They have completed their missions a few decades after launching their electrification programs [33]. Some developing countries, such as Nepal, started approximately 40 years ago, yet more than 60% of its population do not have access to electricity [2]. Nepal may not be able to complete its mission because the economic aspect of a country is the key barrier in promoting increased access to electricity in rural areas. However, rural electrification is not only a technical issue but also a multidimensional phenomenon that is affected by several factors, such as politics, economic development, and culture [34]. Moreover, the outstanding problems of the power ministry are hardly uncommon in almost all developing countries [28,35]. Even developed countries are experiencing these problems [28].

1.3. Benefit of rural electrification

The benefits of rural electrification are not exaggerations [12]. These benefits are evident in remote areas [36], and the implications of these benefits can be measured in rural areas [37,38]. Most studies observed the benefits of rural electrification [3,4,7,10,15,22, 28,29,31,34,39–55] or the negative influence of the lack of electrification in rural areas [43].

Electrification can provide multiple benefits to rural areas:

- Poverty reduction in terms of
  - Welfare. The opportunity for income generation is greater as a result of establishing new businesses or improving existing industry productivity.
  - Energy. The energy needed to operate modern electric appliances, such as TV, fan, and rice cooker, is met. Light is brighter and can be utilized all night.
- Health improvement
  Diseases resulting from the fumes and gases generated from conventional energy resources will vanish and indoor air quality will improve when electric light replaces traditional light sources.
- Securing environmental sustainability
  Emissions from the burning of biomass, diesel, kerosene, and coal through the use of renewable energy resources will be reduced.
- Education improvement
  Children will be provided twice as much time to study in the evenings compared with before electrification.
- Migration mitigation
  People in rural areas will be encouraged to remain in their homelands and use electricity to improve agricultural productivity, small-scale mining, and revive the tourism industry.
- Inequality reduction in terms of provision of electricity services between rural and urban areas

– Reduction of household expenses
– More free time to enjoy social activities and entertainment because manual work becomes mechanized.
– Acceleration of rural economic development

1.4. Rural electrification challenges

Rural electrification is a complicated issue and cannot be solved overnight [22]. Uniting all efforts of government (planning, implementing, managing, and monitoring), private corporations (incorporation and innovation), and rural households (awareness) is necessary to achieve the desired goal of rural electrification.

The following issues hamper the rural electrification program (REP) [2,3,9,10,25,29,31,45,47,56–62]:

– Affordability is the key parameter to achieve 100% universal access to modern reliable electricity services. If everyone can pay for their electricity demands, then the electrification issue becomes a form of supply and demand. However, some rural people in developing countries live in or below the poverty line, in which the main concern is to secure food to survive and not electricity to communicate or entertain. People in this bracket satisfy their energy demand by exploiting traditional, alternative energy resources for lighting and cooking. However, access to grid or owning/sharing of grid generation system in many cases is postponed or repealed because of low household income in rural areas and because of high connection and generation costs.
– Long distance from nearest grid to the rural areas. Although possible, the grid is not a feasible option when other energy generation resources, particularly renewable energy, are available and abundant.
– Inaccessibility. Connection to the mainland national power is impossible when the transportation cost is expensive and when roads and other infrastructure are insufficient, such as for small, scattered, and isolated islands or forests, hill areas, and deserts. For example, Bhutan has a surplus in electricity generation. Therefore, Bhutan exports about 75% of its total generation capacity to India. However, approximately half of the population of Bhutan do not have access to electricity because of its geography. The geography of Bhutan is hilly and harshly mountainous, which makes the building of roads or other infrastructure challenging. This isolated community should evaluate which available renewable resource is the most cost-effective or whether this community may consider using diesel motors.
– Low population densities and dispersed households. Some communities contain only between 2 and 200 households. This pattern of distribution increases the cost of grid connection and makes this option unaffordable for rural communities and unprofitable for generation and distribution companies. The best generation alternative for the randomly distributed population is the utilization of the individual generation system, solar home system (SHS), which is the only system that can generate electricity everywhere on the planet and even in space. SHS can be installed in each household separately to meet individual electrification demands.
– Reluctance of electric generation and distribution companies. Electrification demand in rural villages is typically low. Rural villages require a few watts for fluorescent lamp or for low voltage appliances. Therefore, this low energy consumption among rural villages discourages electric generation and distribution companies to invest in those areas.
– Maintenance responsibility. Determining who is responsible for the maintenance of power generation plays a key role in the success of the REP. Follow-up maintenance is the key to the sustainability of the generating system. [60] discovered that one reason for the failure of the model of the Renewable Energy Service Company (RESCO) in Fiji is the lack of identification of responsibilities, in which parties blame each other and no party wants to be responsible for the poor maintenance of the generating systems. The right and practical way to avoid system malfunction is to hire experts from private sectors to take care of the maintenance responsibility under the supervision of the project donor if the generation system is provided to rural households free of charge or the same scenario but end users pay for the hiring of experts.
– Local society perspective. To evaluate and analyze the potential sources of failures of electrification systems based on renewable energy, [50] researched on program proponents and users and investigated on the relationships between technology and society. Their study revealed that the perspective of local society toward new technology is the main cause of the breakdown.
– Fiscal deficit. Although it can sustain food on the tables of families, traditional business in rural areas (agriculture and grazing) does not increase the income of rural households. Therefore, most rural households have income deficiencies. Consequently, they could not afford to own a generation system or pay for the tariff. Many less developed countries also experience income deficiencies as the rural areas do, in which the lack of liquidity generation (limited financial resources) is the key barrier to their rural electrification targets. For instance, more than 40% of the rural households in Bhutan do not have electricity.
  Less developed countries usually seek assistance from developed countries for loans, grants, or donations. Governments in these countries may be excused when they are unable to provide loans to their citizens to enable them to own a generation system or to subsidize their electricity tariff.
– Poverty of renewable resources. Some rural communities may possess renewable energy resources, such as hydro, wind, biomass, geothermal, and solar energy resources. However, these resources may not be economically or technically viable. Therefore, resources need to be reassessed before installation of any generating system. Communities should not rely only on rough assumptions to avoid improper system sizing due to resource overestimation and to prevent system generating deficiencies and financial losses. Poorly assessed electrification projects gives bad reputation and could not be replicated in similar projects in other communities. For example, most early SHSs for REP in Bhutan have failed to meet the intended demand because of the wrong assumption on radiation data. The project proponents assumed the same radiation data for the entire country all year round.
– Population growth. Given that electric energy is the efficient way to light up the rural household and to power other domestic appliances, this feature makes electricity under continuous demand. In many developing countries, although the electrification rate has increased, the demand for electricity cannot be met because of the increasing rural population [63]. Thus, most of the rural households rely on traditional energy resources to compensate for the lack of electricity [9]. However, despite the efforts of developing countries to keep abreast with the population growth, the gap between population growth and rural electrification will remain significantly large in the years to come [64,65].
– Lack of professionalism. Many early off-grid electrification projects have failed in many remote areas [60,66] because of the lack of qualified skilled technicians to install and maintain the electrification system and because of the difficulty in acquiring spare parts [9,22,60].

– Over dependence on subsidies. Despite the lack of technical or financial capability, the electrification rate in many developing countries such as Nepal remains low although these countries have huge potentials in renewable resources. Developing countries still rely heavily on traditional energy sources and resent their lack of fossil fuel resources. This review considers scarcity of fossil fuel as a reason for the low rural electrification rates in many developing countries. Other developing countries have done much effort to improve their people's access to electricity, and some developing countries still struggle to achieve 50% of the rural electrification rate. For example, China has achieved the top rank in rural electrification rate almost without heavy reliance on subsidies by utilizing local energy resources, by unifying local and central grids, by obtaining government support, and so on. However, to accomplish their rural electrification mission, developing countries need to learn from other successful REPs and adapt suitable programs or modify their programs to suit their needs to secure the sustainability and success of their REPs. The Bangladeshi government has adapted the rural electrification model of the United States, which is based on community involvement. This model was authorized by the Bangladesh REP to supervise the rural electric cooperatives, known as Palli Bidyut Samity. This strategy explains why Bangladesh REP succeeded in their REP.

1.5. Key factors for the success of electricity generation scheme in rural areas

Factors that have great influence on rural electrification, such as user's involvement and ownership, local manufacture, maintenance and management responsibility, and financial support schemes either through government or international donors, are given more attention in [10,22,23,28,29,66].

2. Electricity demand

The demand for electrification will continue [50] for decades to come in rural areas particularly in less developed countries because hundreds of millions of households lack any form of electricity service [9,22,51,62]. Accordingly, [51] introduced a global model to ensure universal access to electricity for all rural households in less developed countries over the next decades and found that the gap to universal access remains large and that universal access to electricity will not be achieved by 2030 in Latin America, sub-Saharan Africa, and in some parts of Asia. For example, more than half million demands for electricity come from rural households in the Brazilian Amazon [22]. Many electrical demands need to be addressed in other rural areas around the world. According to [16], the world needs to produce 10 times the global electricity consumption to reach universal access to electricity to light up the entire world at 1 kW per person [16]. This finding indicates that the pressure on electricity generation energy resources will continue to increase globally and remain in short supply. The demand–supply gap increase is mainly caused by population growth [9]. [67] forecasted that in the following two decades, the world electricity generation is expected to increase by 84% from 2008 to 2035, which indicates that electricity has the fastest growing demand as an end-use energy worldwide in the midterm run than consumption of liquid fuels, natural gas, or coal in all end-use sectors except transportation.

2.1. Drivers of demand

Many factors affect electricity demand, such as weather, economic growth, social and demographic factors, end-user prices and subsidies, policy factors, technological development and energy conservation, industry structure, energy intensity, energy savings and demand side management, peak load and seasonal variation, population growth, industrialization, and urbanization [69–71].

2.2. Right of access to electricity

Access to electricity has become part of the basic human rights that needs to be fulfilled and established within the framework of international and national human rights laws [68], thus permitting all low-income households basic access to lighting, information, communication, leisure, and security [22]. This paper argues that 50 kW h of electricity per month should be given to low-income households. In 2003, the South African government introduced free basic electricity to assist low-income households [15] and 1000 kW h as basic annual access to electricity per capita until 2100 [43,69].

2.3. Electricity demands of rural households

The electricity demand in rural areas significantly depends on affordability, which is influenced by income, feasibility, and availability. Electricity demand is also influenced by the amount of electricity generation resources, which are influenced by site characteristics particularly for renewable energy. However, rural households have low electricity demand. For instance, 10 W is considered a light package per household in Kenya [70]. [75] denoted that 50 W per household is sufficient in Kenya. [41] denoted that 75 W is the average daily energy requirement per household and that this amount of energy has a significant positive influence on the lives of people in the rural community. These few watts are more than enough and can provide survival indoor lighting services for remote and inaccessible areas such as the *Humla* communities in Nepal [42].

However, for a community where the grid connection seems to be the only option, tariffs should be set extremely low [71] to assist and enable low-income households in less developed countries to afford the service because grid connection capital costs are still beyond their means [21,29]. This condition signifies that without subsidizing electricity generation, grid connection for low-income households is likely to be unfeasible [29].

3. Obtaining access to electricity among low-income households

Low-income households in remote areas have several options to choose from for generating electricity. Selecting the right technology is important [9]. End users obtain the most cost-effective option that sustains their electricity demand. However, preference for one option over others depends on the following factors: type of energy source available [9,72], rural economic development [25,72], disposal of residues [72], economic feasibility [9,31], nature of the end-use application [9], and government programs and policies [25]. Batteries, diesel generator, pedal generator (PG), pico hydro, photovoltaic (PV) SHS, and wind are the energy sources seen in rural communities.

3.1. Batteries

Currently, technology offers many types of batteries for different applications, such as applications and components in watches, mobile phones, rechargeable lanterns, cars, and huge battery charging stations. Among the energy sources available, the rural population considers batteries as the easiest mode of access to electricity [21,70]. Low-income households have been using batteries for light loads, such as for lighting their radios and TVs, which were operated for a few hours during the night because of their low electric capacity. Furthermore, batteries can deliver between 5 times and 15 times more brightness than the traditional kerosene lamps can [21]. Considering that the rural community lacks technical capability and has poor economy, the costs of grid extension, diesel generator, and renewable energy resources (e.g., solar and wind (regardless of their huge potential)) have become prohibitive [3]. Although batteries are preferred by rural households because they prefer to pay as they consume, the cost of electricity when using batteries is higher than when using grid or renewable energy technologies.

Dealing with batteries could be dangerous and may cause serious injury in areas where few recycling programs exist, such as in isolated areas. Batteries have high lead and sulfuric acid contents [70]. Sulfuric acid is a toxic and harmful compound that can burn the skin upon contact and can destroy the digestive system if swallowed. This condition is detrimental because injuries caused by batteries are often left unattended and may worsen. Immediate medical attention is difficult in remote rural areas. Batteries may also produce hydrogen gas, which may ignite and explode in the presence of flame or spark.

The following are the advantages and disadvantages of using battery as an option for generating electricity in the rural community [70].

Batteries have some advantages over other energy sources. The main advantages are the following: fast access to electricity, no pre-installation work needed, independent from either site-specific or source availability, suitable for loads used frequently, low capital cost (70 USD), low life-cycle cost (136 USD), and no potential electric shock occurrences due to low voltage (12 V).

The main weaknesses of batteries include the following: too expensive for larger loads or continuous usage, high cost of regular transportation, and expensive recharging fee. A typical recharge fee from a grid-connected recharging station could amount to approximately 0.2 USD to 0.64 USD per recharge [70,73]. Battery misuse may lead to its rapid decline in performance and lifetime. A battery requires more care when regularly used because of its charging and discharging period, as well as its short lifetime of two years, its high annual operation and maintenance costs (33 USD), and its high electricity cost per kW h (4.36 USD).

3.2. *Diesel generator*

Using diesel-powered generator sets has been the widespread traditional solution to improve the access to electricity among rural households for decades [6,74–78]. Diesel-powered generators sets are mainly preferred because of their low capital cost [23,26,75], simple technology [76], no civil work preparation required, short installation time [23,75], flexibility to meet the low rural household demand from a few hundred watts and above [22,76], and household inaccessibility in which the grid will not be considered [75]. In general, the advantages of using diesel-powered generators are appreciated when considered from these points of view [74,76,79]:

Diesel-powered generators produce alternating current (AC) directly and provide larger amounts of power than other options do in terms of cost per kW. Diesel-powered generators also have lower investment cost per kW compared with hydropower or wind and have fast start-up capability to provide energy any time, thus making them ideal for emergency applications. For example, Ref. [26] studied the economic viability of stand-alone, household-sized renewable energy technologies, namely two solar PV systems of 100 Wp and 130 Wp, 150 w wind generator and 450 w gasoline generator stated that gasoline generator is the lowest total capital costs among the mentioned renewable options in terms of cash per watt SHS100 w=USD5.9/W, SHS 130 w=USD5.7/W, wind generator150 w=USD1.8/W and gasoline generator 450 w=USD0.8/W, unfortunately its fuel consumption cost and low capacity factor are the main reasons for not providing electricity with cost effectiveness.

Diesel-powered generators are commonly used when the electricity generating site fails to meet the intended demand as a result of seasonal variation of the site or increases in the power demands of end users. Ref. [76] analyzed the field performance of different off-grid generation technologies applied to the electrification of rural area of the province of Jujuy, northwest of Argentina. These technologies include five hydro-diesel hybrid systems that supply electricity to rural community between 80 and more than 300 households. The study found that the hydro turbine, which is one of the hydro-diesel hybrid systems, supplied only 10% of the total power generation. The deficiency is supposed to be from the increasing energy demand, but [76] determined that the weak supply is mainly caused by the yearly variations of water availability. In the same site, the recent increase in the electricity demand compelled the community to install a new diesel-powered generator to meet the new demand. Given that only hydropower is available, repowering the hydro site once developed is impossible. The only fast start-up option to meet the increasing demand is to use a diesel-powered generator [76]. Diesel-powered generators are the most expensive option for generating electricity [22,23,26,46,80]. Diesel-powered generators are avoided and not preferred by rural households or for REPs [28] because these generators have limited load satisfaction and access. In addition, these generators are inapplicable to areas where generated electricity is only needed during the night (6 pm to 10 pm) [7,16,22,26,35,81]. The high tariff charge [35] and high diesel fuel cost also make diesel-fueled generators inapplicable to rural households. An additional cost of up to 50% is added to the market price of fuel for its transportation because of the lack of adequate infrastructure in remote areas. Transportation cost depends on site distance and accessibility [16,22,23,26,46,75,76,79,81–86]. Sometimes users need to invest to store large amounts of fuel for months during rainy seasons [76]. Diesel-fueled generators also have low capacity factor [26], weak productive utilization [87], and short system life spans [46,75]. Given that diesel-powered generators works under the principle of reciprocating internal combustion engine [88], these generators burn fossil fuel to produce torque to generate electricity. Diesel-fueled generators tend to have the highest CO_2 emissions among other power sources because this source burns up fossil fuels to generate electricity. This process accompanied by the emission of greenhouse gas [7,28,31,88] affects the environment negatively and has been given much focus at the global and local levels [23,76,80]. Moreover, diesel-fueled generators are associated with high cost of maintenance and operations [7,28,85] as a result of its moving components. Thus, diesel-fueled generators require skilled technicians and require more regular maintenance and repair than SHS does [31,79]. Maintenance can cause stoppage in electricity services and adds extra costs [37,75]. In addition, high noise is generated [88] as result of the moving parts.

3.2.1. *Alternative fuel for diesel-fueled generator*

Some researchers found that biofuels, such as landfill gas and straight vegetable oil from Jatropha, could be used as good substitutes to diesel-fueled electricity generation [6,45,87]. For instance, according to [6], the human labor requirements in rural electrification using Jatropha oil and the tariff for using Jatropha oil to generate electricity are several times greater than the tariff provided by the national government. In addition, [6] denoted that subsidy is the key role for project feasibility. Using biofuels as alternative to diesel has raised other challenges, such as food security and environmental influence [87], even though access to electricity bring many benefits to rural communities [6]. For instance, millions of people in China benefit from REP [29]. On the basis of the number of people who can be involved in the intensive labor of planting, harvesting, and de-hulling Jatropha [6], employing human muscles as prime movers in electricity generation could be the perfect solution for the electrification program in rural areas from the energy generation perspective.

Using fossil fuel to electrify rural areas is a forced choice considering the high cost of fuel and transportation [22]. This option is no longer recommended for low-income rural households [75] and is avoided by many donor organizations, such as the World Bank [79,83]. Such use in rural areas has been limited [28] because it is neither economically nor environmentally friendly in remote areas [89].

However, the only chance of using diesel-fueled generators to generate electricity for rural households is when the site is inaccessible [22], when grid extension is impossible, when sustainable renewable energy resources are not available [75,89], or, in the case of most oil-producing developing countries, when the diesel-powered generator is the first option for the REP [27] even when considerable renewable resources are available. The latter is mainly attributed to the low cost of oil in such countries, where the government usually subsidizes the oil price, uses oil as a backup for other types of electricity generation, or forms a hybrid configuration with renewable resources for electricity generation [8,82,90–92].

3.3. Pedal generator

PG is the most suitable power source for remote communities, where extremely low-income households usually live and renewable energy sources are neither available nor viable [93]. For instance, PG is the most suitable power source for the villages of Thulo Pokhara and Raje Danda, Nepal because of the following reasons [93,94]: continuous operation (24 h/day) with simple technique; approximately 100 CAD capital cost of lighting a Nepali home; low cost, which can be achieved by cost-sharing (PG can light more than 20 homes simultaneously); safety (only 12 V of electricity); simultaneous charging of multiple batteries; ease of maintenance, repair, and transportation to remote villages; local manufacturing; short-duration energy generation (i.e., around 30 min or less of gentle pedaling for each home).

The following are the main drawbacks of the PG: physical work for recharging; daily recharging (i.e., pedaling) time of around 30 min; risk of children playing with and misusing the PG, which has moving parts that might be attractive to them; incorrect connection to the PG of battery in charging mode, which can damage the system. Furthermore, the storage battery is an essential component. In addition, the battery is replaced every six months [94].

3.4. Wind

Over the last two decades, wind energy has significantly moved forward as a clean, efficient, and cost-effective energy source [7]. Wind energy developers have used the latest advanced technology [50] to improve wind turbine design for maximum harvesting of wind energy and for the optimum performance of wind turbines.

Ref. [95] developed a new wind power technology inspired by aerospace technology. This wind turbine is designed according to the principle of jet engine instead of traditional windmills and is four times more efficient than traditional rotor blade turbines are. Interestingly, an Italian private company introduced a new way of utilizing wind energy by using Kite Gen Stem, which uses flying kites at high altitudes (2000 m) for optimum harvesting of wind energy, in contrast to traditional wind turbines [96].

Despite the fact that, developer's efforts have facilitated harvesting of wind kinetic energy to generate electricity which accelerated wind market to its large growth, Ref. [97] expected that until the projection period of 2030, wind energy is not able to compete economically with fossil fuels and hydroelectricity.

Such technological developments and idea have failed to make wind turbines affordable for rural households and have failed to make wind turbines become cost-competitive with other renewable energy resources, such as water [97]. The decentralized wind turbine is a less popular technology for single households in rural areas [23,90] because this technology is site-specific [5] and has very high cost of turbine (i.e., about 6903 USD/turbine) [27]. In contrast to solar energy, which can be exploited on almost any surface of the planet [34,98], wind and hydro are both site-specific [5]. Once the site has been developed, substitution is no longer possible. Aside from such similarity, wind and hydro also use turbines to convert kinetic energy into electrical energy and require head for higher energy production. For example, the wind turbine should be constructed on a location with the highest wind resource, usually at high altitudes, to guarantee greater energy utilization. This requirement is similar to that of hydro, which needs high head for higher energy production. Despite the many similarities, a wide gap in cost-effectiveness exists among the options for rural electrification, of which the hydro is the most cost-effective [70,81,89,99–104] and favorable for rural households and is supposed to be checked first [89]. However, the feasibility of using wind turbines is basically dependent on natural variations in wind speed on the site [26]. Using wind turbines for electricity generation are distinguished by a lifespan of up to 20 years in harsh environments, higher cost-effectiveness than PV or than diesel/gasoline generator if locally manufactured, AC production, easy management, low maintenance cost, and option of single household use or community sharing [23,26,97,105–108]. However, small wind turbines also have many shortcomings [23,26,90,97,105–109], which prevent them from being used by rural households. Lack of wind resource and wind variability is the greatest challenge in some less developed countries. High investment cost is another disadvantage, which limits the affordability and dissemination of wind technology in rural areas. The installation cost of small wind turbines of up to 1.0 kW in the United Kingdom is around 2000 GBP to 6000 GBP, whereas the larger systems of 2.5 kW to 6.0 kW cost ranges from 12,000 GBP to 20,000 GBP. Moreover, component fatigue frequently occurs because of cyclic loads caused by variations in wind speed. As wind speed increases, the turbine needs to be shut down to avoid twisting or breaking of the turbine into pieces. If the turbine survives failure or damage, the turbine will suffers from poor performance because of wind speed variation. Given the considerable wind speed variation, the power generated is changed accordingly; thus, storage is crucial. Turbines also need to be positioned at high places, where most wind energy is available to maximize the exploitation of energy and in order to avoid obstructions, such as trees, buildings, and constructions, in the path line of the wind to the turbines. Therefore, turbines can be called outdoor energy exploitation systems, in contrast to hydrosystems, which can be covered (pico) or found in a powerhouse (small/large hydro). Turbines are exposed to thunderstorms, lightning, and corrosion from heavy rainfall, wetness, and high salinity. The rotating blades of wind turbines also kill many birds every year. Moreover, wind turbines are noisy and influence visual amenity.

3.5. Solar PV

Solar energy is the most abundant energy source on earth [106,110]. Solar energy generates other forms of renewable energy and is an unlimited and clean resource available in the entire planet [34,59]. PV is the fastest growing energy technology in the world for single households in rural areas and is perceived to be moving at a fast pace toward progress and maturity [47,59,110,111]. SHSs are the most popular PV applications, dominating rural generation technology and adopted globally to meet the basic electricity demands of households in rural areas [47,50,88,90,91]. SHSs now serve millions of people in rural areas around the word [112]. Hundreds of thousands of SHSs have been used as modern electricity generators in rural households around the world to replace smokey fuels (e.g., candles, kerosene lamps, and gasoline/diesel-powered generating sets) and interrupted, unreliable grids [88]. According to [113], estimating the number of SHSs currently in use is difficult. For example, over 400,000 and 200,000 systems have been installed only in rural China and Bangladesh, respectively. In the past decade, 100,000 SHSs have been sold in Kenya [114]. In 1997, between 100,000 and 200,000 SHSs were sold in some developing countries [34]. The government of Bangladesh has installed 500,000 SHSs to respond to the electrification demand resulting from rural population growth [58]. By the end of 2007, approximately 115,000 SHSs were installed in Nepal [115]. By the end of 2010, more than 13,000 (80 Wp mono-crystalline silicon cell PV module) SHSs were installed in 12 provinces in Morocco for its decentralized REP [116]. More than a million SHSs have been installed to electrify rural homes in developing countries [117,118]. Despite its technological benefits, PV systems are not cost-effective energy options for rural electrification because of their high capital cost [46,119–121]. PV systems also cannot compete economically with existing grids [122] or other renewable sources of energy, such as hydro or wind. The key influence in the continuation of this technology is government subsidy, the lack of which could end of the deployment and acquisition of the technology [47,60,115,119]. [115] concluded that solar PV systems cannot compete yet with grid electricity, even if the country has abundant solar energy, such as Nepal, and suggested that as long as urban households can afford access to grid electricity, they should stay connected to the grid and not resort to alternative solar PV systems. [123] compared wind and PV stand-alone power systems used for the electrification for remote consumers and found that wind systems are more preferable over PV systems in locations where both wind and solar energy are abundant. [70] advised communities in isolated areas with no access to grid electricity to explore and exploit their renewable energy resources for their electricity demand in the medium term. This suggestion is sound because renewable energy is the most cost-effective option for rural electrification, followed by grid extensions [80]. These communities should utilize pico hydro wherever suitable sites exist because its cost per kilowatt hour is less than 15% of that of the cheapest SHS [70]. Although the cost of PV has declined [47,70,124], some countries with enormous potential for utilizing solar energy still rely on imported oil with high and unstable prices as a source of energy. These countries do so because PV is still not affordable for rural households [112] because they lack skilled technicians to install and maintain the equipment and have difficulties in acquiring spare parts [9,22] or because fuel is cheaper due to national subsidy. In the absence of pico and wind for low-income households, opportunities to opt for PV arise as long as governments provide subsidy or funds [47,112] and as long as the generator set is connected to incandescent lamps and not to tube lights or compact fluorescent lamps [124].

However, grid extension may not be considered in the near future or is practically impossible in situations where a few watts of electricity demand are used to produce light and operate small home devices in remote areas. In areas where natural resources (hydro and wind) are not available and the other option is not affordable (diesel), battery charging SHSs are the only option left for rural electrification [121,125], provided that financial support is available.

PV systems have many potential benefits. For example, no civil works are required to install the scheme [119]. PV systems are easy to install and run, require less maintenance, and have very low maintenance cost [56,59,88,90,98,107,119,121]. They are portable and light to facilitate transportation to end users in remote locations [59,88,119]. PV systems generate direct current (12 V) [59,106]; thus, electric shock is not produced. PV systems are easy to manage even if owned by more than one household and has a quiet mechanism, with no moving parts that emit irritating noise [56,107]. Moreover, PV systems are associated with a lifespan of up to 25 years [27,56,70,75,88] and are environmental-friendly, with little environmental effect during its functioning lifetime. For every 1 kW h of power generated by the PV, carbon dioxide is reduced by 0.7 kg, which is supposed to be emitted to the air in case any smoldering fuel resources are used [56,59,107]. Most SHSs in rural areas are owned by individuals. Therefore, no load limiters are required in each house to prevent consumers from bypassing their packages. Consequently, conflict among communities can be avoided. Management and staff are not needed for the operation and maintenance of the shared SHS and for tariff collection, respectively [126]. SHS also does not burn fuel that produces emissions, although the greenhouse gas emissions of its transportation and manufacture are part of its total environmental emissions [112]. However, [112] claimed that those minor indirect emissions can be ignored because SHS makes a considerable contribution to climate change mitigation.

Finally, electricity generated by PV mainly depends on the area of the panels, a feature that gives PV more flexibility than other options in responding to future demand [59,76,91]. Thus, PV can be repowered to limit fuel expenses for the diesel generator to meet additional demand [59,76,88,91]. With these advantages together with financial support and the scarcity of other generation alternatives, many rural households have considered PV as an attractive option for electrification [47,88].

However, PV systems also have disadvantages compared with other options. PV systems can be used only where direct current (DC) is available [70,106,127]. Power generation also depends on the intensity and duration of solar radiation [56,59]. As a result, batteries are required for electricity storage to maintain current continuity and supply electricity during the night or when sunlight is insufficient because of physical obstructions [56,90]. These batteries cost about 300 USD/kW h [98] and need regular replacement [121,128]. Despite the high cost and low lifespan of batteries (i.e., three years to five years) [56,106,129], PV systems have huge losses, approximately 40% of which are accounted for by batteries and other components [89,24]. Moreover, PV users deal with chemical hazards that threaten the environment with no proper hazard control [56,106,129]. PV cells also contain cadmium telluride, a toxic heavy metal and carcinogen [107] [35]. Furthermore, PV is a site-oriented system; thus, perfect orientation is not always achievable where environmental and weather obstacles exist, such as trees, mountains, buildings, wind, snow, high temperature, and airborne contaminants, which might shade the modules and impair system performance [59,70,86,107,129]. In contrast to other options, PV needs a large area for electricity generation. For instance, each 1 kW p generated requires approximately 8 m^2 to 10 m^2 of roof space [56,107,130]. These large areas require frequent cleaning [107] from dust or bird waste.

These issues have a negative influence on PV system performance, which explains why PV technology is more cost-effective in sunny locations [59,106].

3.5.1. PV system and energy costs

Although PV is the most commonly used technology for electrification in rural areas in many developing countries [47], many rural households cannot afford PV [25,56] because of its high capital cost [25,46,56,60,70,90,110,131]. The capital cost of PV panels ranges from 4000 USD/kW to 6000 USD/kW [27,56,59, 90,98,110]. For complete PV electrical systems, the costs can reach 100,000 USD/kW [98]. In Morocco, the overall program cost reaches 21 EUR/Wp or 1574 EUR/SHS [116].

3.5.2. Energy cost of SHS

Among renewable energy technologies, PV technology produces the highest cost per watt [60,70,131]. However, the cost of energy generated by decentralized PV ranges from 0.45 USD/kW h to 2.10 USD/kW h and is influenced by many factors, such as transportation, taxes, system efficiency, climate, and season [52,132]. For example, in a 13,000 SHS REP in Morocco, SHSs were provided with a fee of 1.73 USD/kW h [116].

The high PV scheme and energy generation costs are likely to be the main barriers to the widespread use of PV in rural areas in many developing countries [46,56,90].

3.6. Pico-hydro power

Pico hydro is the smallest hydropower plant [94,99,133–136], with a capacity of less than 5 kW [100,133–138]. Pico hydro is known as “family hydro” in some countries because they can be owned by a single household [99,133,136]. The simplicity of pico hydro technology [70] has attracted the attention of many experts and even non-experts interested in generating electricity from renewable resources. Considerable attention has been given to pico hydro technology because it is seen as a cost-effective and promising option for supplying electricity to rural areas [70,81,89,99–104]. The pico hydro scheme is the most cost-effective option among off-grid options (wind, PV, diesel generator,…etc.) for rural electrification whenever a pico hydro site is available [70,81]. The suitability of this technology should be urgently ascertained [89].

The following are the most famous pico hydro turbines for off-grid electrification in rural areas: Pico Power Pack, Peltric turbine, low cost DC pico hydro system, Stream Engine, Turgo turbine, PowerPal, axial and cross-flow turbines, and pumps as turbine.

The design of pico turbines can hardly be modified to improve performance [81] because hydro technology is a rapidly maturing technology [133] and because hydro technology is one of the oldest energy sources known to mankind and the first one used to generate electricity [139] with an efficiency of up to 90% [140].

Schemes on making pico turbines affordable should be made, such as offering long-term funds. Such schemes have been successful among low-income households. [70,134–136,141–144] discussed the factors in the success of hydro pico schemes for rural electrification in less developed countries and employed pico in new applications or usages (e.g., an energy recovery device) [145,146].

Although the main users of this technology are low-income households, multimillion-dollar companies such as Motorola have found PV an attractive and interesting alternative to grid and other renewable options for wireless communication network base stations in remote areas [147]. Ref. [148] discovered an interesting application for pico turbines in utilizing the kinetic energy of the water that flows through domestic pipes and using it for battery recharging.

The main advantages of pico hydro technology are sustainability, low maintenance and scheme cost (about half that of PV) [2,147], sharing [100,133], flexible design, option for local manufacturing, and easy installation, operation, and maintenance [94,135,136]. As an energy-utilizing device [145,146], pico hydro is an environmental-friendly energy resource [149].

Pico hydro technology is similar to other renewable technologies in terms of site availability [2,81,140,150,151]. Pico hydro technology requires more civil work than others, which is likely to increase the total cost of the scheme [70,140]. Despite the maturity and significant improvement of this technology, flow rate fluctuation is still one key challenge faced by hydro power systems in dry season (minimum power production) and monsoons (turbine shutdown to avoid being washed away) [152]. Given that hydroelectricity is mainly based on the head and flow of the site [75], room for upgrading the scheme rarely exists once the turbine is installed. As a result of flow rises and falls, power supply in many hydro sites cannot meet the yearly projected demand [75]. Combining the pico hydro with the hybrid system, which is another power generating source, can satisfy the intended demand and maintain power continuity all year long [75].

Pico hydro has a large potential global market in less developed countries, which is estimated to be around 4 million units [153]. Even in more developed countries such as Japan, considerable interest has been given to this technology because of high tariff and because this technology is considered an individual contribution to lessening climate change [154].

4. Average daily basic electricity affordable cost for rural households

The average cost of electrifying one rural household is about 2000 USD [9,60]. Thus, rural households can afford to pay for access to electricity by lengthening the payment schedule of the electrification cost and dropping the interest rate and taxes if any [1,60]. If the government, World Bank, or other international agencies provide a 20-year (product lifespan) slow and low soft loan payment without interest to offset the high capital costs, then users who cannot afford the full costs of PV will be able to afford access to electricity [8]. On the basis of the average cost of electrifying one rural household, households will pay 0.27 USD daily for basic electricity services, which is less than seven times the daily amount charged (2 USD) to some rural households in Ethiopia for using three 60 W bulbs from a diesel generator for only 3 h a day [35]. This amount is about the same as the annual cost (including that of spare parts over a 20-year service life) in rural Morocco under the 13,000 SHS REP [116] and in Fiji, where the government owns and rents the SHSs to rural households and provides maintenance through a public–private sector partnership [60]. The last model has been replicated in many countries, but in Fiji, the model did not meet the goal of the program because of the failure of sequential governments to implement the RESCO program originally proposed by donors. Despite its problems, the RESCO model in Fiji seems to be more applicable where electricity is affordable, given that the user pays less monthly and the government owns and rents the SHS and assures maintenance through a private sector under their supervision.

5. Recommendations

5.1. Maintenance along the lifespan of the system

Despite the maintenance cost, which in some generating systems such as the SHS is equivalent to the installation cost [116], the sponsor should provide long-term maintenance to prevent system malfunction and breakdown and user misuse, to sustain scheme operation, and to encourage rural households to take care of their systems.

5.1.1. Households own and government follows up

One option is households owning the electric generation system by paying with their own money or with financial support (e.g., subsidy, loan, and grant) from the government or international donors. The government should provide maintenance of the system. In this scenario, the cost of warranty (if any) should be replaced by term regular check and maintenance to build a strong bond between renewable energy technologies and end users and disseminate such technologies in other remote areas. Follow-up for regular check and maintenance should be held quarterly. Maintenance could be run by government institutions or authorized agents. This suggestion is expected to work in rural India because rural electrification is the responsibility of the Ministry of New and Renewable Energy.

5.1.2. Households rent and government follows up

When the electric generation system is far beyond what rural households can afford and when the economy is weak, the government should own the system or rent it from investors with tariff subsidy to provide rural people with access to electricity or mandate investors to rent the system directly to rural households with the same above conditions. This suggestion seems to be preferable for most rural areas in developing countries, particularly in sub-Saharan Africa and some parts of Asia.

6. Conclusion

Rural areas suffer from energy poverty and lack of human and economic development. Renewable energy, such as pico hydropower, solar PV, and wind turbines, is the most promising option for feasible, sustainable decentralized rural electrification generation systems, particularly in rural areas with massive renewable energy resources. This option should be considered because of the high cost of grid electricity and transportation cost of fossil fuel to remote areas (along with increased fuel market prices), as well as the environmental concern about the exhaust of burning fossil fuel. Provision of affordable electricity to remote households is an essential aspect of human and economic development in rural areas worldwide and an obligation of governments toward their citizens. For many developing countries, this obligation is a huge challenge because of their weak economy, which is a key barrier to rural electrification. Thus, developed countries should not be perplexed in assisting less developed countries in their renewable resource-based because low-income households in these countries need merely a few watts for their daily energy demand. According to the availability of electricity generation resources in rural areas and to the selection criteria of feasibility and sustainability, pico hydro is the top choice of rural households, followed by wind, PV, and diesel-fueled generators. Although pico is the most cost-effective option, PV is the most dominant renewable energy technology for rural electrification because of the availability of solar energy resource all over the world.

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